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Saving Energy in Refrigerated Warehouse

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Compression refrigeration plants are used widely in refrigerated warehouses. Most commonly, they are driven by electric power. The electric power drives the compressor, pump and fan motors. Therefore, to reduce the electricity bill of refrigerated warehouses, one method is to improve the efficiency of the electric systems of the plants. Improving the power factor is an important method for improving the efficiency of electric systems. This is not a new discovery. However, based on a 1999 survey of refrigerated warehouses conducted by the authors in the United States and Canada, the issue of improving the power factor was often overlooked. The measures and potentials of energy cost savings by improving the power factor are discussed in this article. A case study based on the survey follows.

Power Factor

Almost all motors in industrial refrigeration facilities are AC induction motors operating on threephase and 460 V. Thus, this discussion only refers to these motors.

The current of an AC induction motor has two components: active and reactive. The active component is responsible for the torque and work performed by the motor. This component is small at no load and rises as the load grows. The reactive component creates the rotating magnetic field. It is almost constant from no load to full load, as is the magnetic field. Although the reactive component does not perform useful work, it is required to excite the motor to create the rotating magnetic field. It has to be supplied by the power network. The ratio of active to total current is called the power factor. It also is represented by the ratio between the real power (measured in watts or kW) and apparent power (the product of the voltage times the current measured in volt-amperes or kVA).

The power factor is expressed either as a decimal fraction (from zero to one) or a percentage (0% to 100%). In the case of pure sinusoidal waveforms (those not distorted by harmonics), the power factor is equal to the cosine of the phase angle between the voltage and current waves in an AC circuit.

Since cosine values range from 0 to 1, the apparent power is always greater than or equal to the real power. When a motor is operating at no load, the energy absorbed by the motor is limited to the power losses (motor inefficiencies), so the active component is small and the power factor can be as low as 10%. At full load the active component is at its maximum, so the power factor is typically 70% to 95% for a threephase motor. A high power factor is desirable because it implies a low reactive power component. A poor power factor has the following effects:

- Higher losses in the cables and transformers, and thus higher energy bills for a given amount of useful work output. For example[1], increasing the power factor from 0.75 to 0.90 reduces cable and transformer copper losses by 32%.
- Reduced available capacity of transformers, circuit breakers, and cables, whose capacity depends on the total current. The capacity falls linearly as the power factor decreases. A 1,000-kVA transformer supplying loads with a 70% power factor only is able to supply 700 kW.
- Higher voltage drops, yielding problems associated with undervoltage.
- High power factor penalty charge assigned by the utility.

Figure 1 shows the relationship of power factors. The vertical, downward arrow represents the reactive component (kVAR) of the power. When the power factor angle is corrected from θ to φ, the reactive component will decrease from $(kVAR)_\theta$ to $(kVAR)_\varphi$. At the same time, the total power will be decreased from $(kVA)_\theta$ to $(kVA)_\varphi$ while the working power (kW) remains the same.

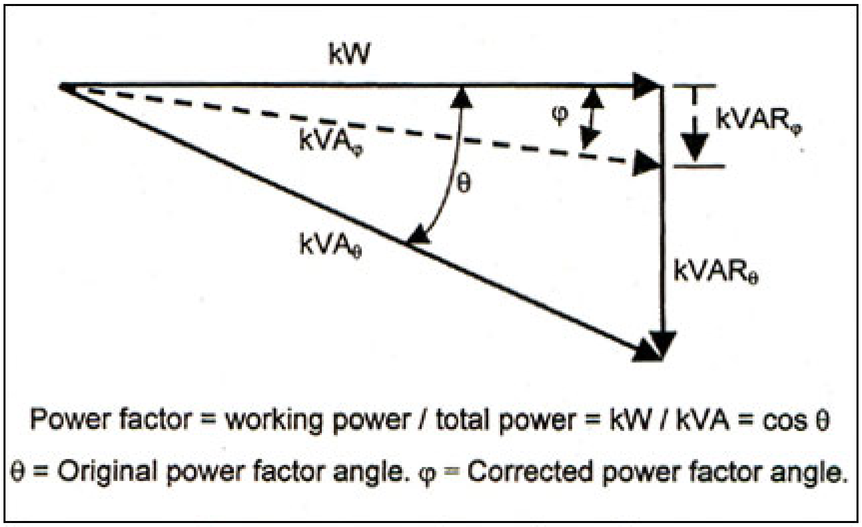

Figure 1 : Power factor relationships

Conditions Affecting Power Factor

For a given electric motor, the efficiency and power factor vary with the load as well as with some other factors, such as supply voltage. The power factor drops steadily with decreasing load and it drops sharply below 60% load. Thus, the power factor is affected by the actual load of the existing motors. The lower the actual load, the lower the power factor. Therefore, it is important to reduce the power factor losses towards lower loads, particularly if the actual load drops below 60% load.

After measuring 1,000 (mostly industrial) motors, Labodosky,[2] an engineer at Pacific Gas and Electric, concluded that "Half the motors in the real world are operating at less than 60% of their rated load, and a third are operating at less than half their rated load."

In industrial refrigeration plants, the light load of motors is based on two cases. In the first case, the installed motor is oversized for the given application by the designer. The second case takes place during part-load operations. Modern refrigeration compressors (reciprocating or screw) commonly are equipped with unloading devices. When the mass flow rates are small or the compressors are unloaded, the motors are lightly loaded.

A survey[2] in the United States found that industrial facilities, where most of the electric load is used for motors, will typically have plant power factors of 70% to 80% without power factor correction. Another survey3 in China found that the natural power factor (without power factor correction) in refrigerated warehouses ranges form 60% to 80%. Thus, the occurrence of low power factors is quite common.

Handling Excessive Power Factor Losses

A watt-hour meter only records the active power of the electric circuit. However, the apparent power (total power), which consists of active and reactive power, must be supplied by the electric utility. Therefore, most utilities penalize consumers whose power factor is below a threshold level, typically in the range of 85% to 95%. Thus, when consumers improve the power factor, they reduce both the penalty charges of their energy bill and the reactive power bill. The savings from avoiding utility penalty charges are typically larger than the energy savings from power factor correction.

Even when the motor sizes are correct, often (as stated earlier) the motors in refrigeration plants will operate under a light load (low power factor). Therefore, the more popular method of improving the power factor on low-voltage electric distribution systems is to correct the power factor by some measures. Many devices are available for power factor correction. Three of the more common types are capacitors, synchronous motors and synchronous condensers. Synchronous condensers are the most expensive and are not a practical solution in most cases.

In motors and other inductive loads operating in AC circuits, the current wave lags behind the voltage wave. When a capacitive load is applied to an AC circuit, the voltage wave lags behind the current wave. Since these are opposite effects, they can be used to cancel each other. Capacitor correction is relatively inexpensive both for material and installation costs. Capacitors can be installed at any point in the electrical system, and will improve the power factor between the point of application and the power source. However, the power factor between the utilization equipment and the capacitor will remain unchanged. The advantages and disadvantages of each type of installation are listed in **Table 1**.

The most economical installation for a particular plant depends on the utility rate structure cited for the plant. Try to obtain as much information as possible about the current and future rate structures before attempting to reduce costs by power factor correction measures.

The methods of improving the power factor stated earlier are applicable for constant speed motors and may not be applicable to motors connected to variable speed drivers. However, the variable speed driver, especially if connected to a computerized control system, may be able to control the current and thus, the power factor directly.

Table 1 : The advantages and disadvantages of different installations of capacitors[4]

Individual Equipment

Advantages

- Increased load capabilities of electrical distribution system.
- Can be switched with equipment, thus no additional switching is required.
- Better voltage regulation because capacitor use follows load.
- Capacitor sizing is simplified.
- Capacitors are coupled with equipment. They move with equipment if changes are made.

Disadvantages

- Small capacitors cost more per kVAR than larger units (economic break point for individual correction is generally at 10 hp).

Grouped Equipment

Advantages

- Increase load capabilities of service.
- Reduced material costs relative to individual correction.
- Reduced installation costs relative to individual correction.

Disadvantages

- Switching means may be required to control amount of capacitance used.
- Does not improve the load capabilities of the distribution system.

Main Service

Advantages

- Low material installation costs.

Disadvantages

- Switching means will be required to control the amount of capacitance used.
- Does not improve the load capabilities of the distribution system.

Table 2 : Power factor and capacitors in 62 plants

	Without Capacitors	With Capacitors	No Answer
Plants w/o & w Capacitors	58% (36 plants)	32.3% (20 plants)	9.7%(6 plants)
Power Factor	0.75 – 0.91(?)	0.85 – 0.98	53.2% (33 plants)

Actual Power Factor in PRWs

With the support of the International Association of Refrigerated Warehouses (IARW), a survey on energy efficiencies (including power factor) of public refrigerated warehouses (PRWs) was conducted from January 1999 to September 1999 in the United States and Canada. The survey was conducted using a questionnaire and field investigation. A total of

62 responses were collected. In addition, a field investigation of 14 plants was conducted. The status of the power factor and the use of capacitors as determined by the survey[5] are shown in **Table 2**.

As stated earlier, the power factor without correction is usually between 0.6 to 0.8. Therefore, it is unlikely that the power factor is more than 0.85 as indicated by some responses, without power factor correction. Responses indicated that most plants (up to 58%) did not install capacitors. Fifty-three percent of the plants surveyed did not answer the question about their value of power factors. This result compares well with the field survey that was conducted as part of the project. During the field investigation, half of the engineers did not know the power factor of their plants.

A Case Study

As part of the field investigations within the survey project, a plant was visited that did not install capacitors. The plant has a normal power factor of 0.8 and a total of 1,700 kW motors are installed to drive the refrigerating compressors. This plant will be used as an example to evaluate the result of adding capacitors. This case study is dependent on the utility rate structure and the results would vary by utility.

The installation cost for electric capacitors ranges from $20 to $30 per kVAR of reactive power for dispersed units.[1] If a utility increases the demand charge by 1% for every 1% the power factor drops below 90%, the plant will be charged for peak demand as follows:

Adjusted peak = (1,700 kW) x [1 +(0.9 – 0.8)] = 1,870 kW

If the demand charge is $70 per kW-yr, the power factor penalty charge will be:

Power factor penalty charge = (1870 – 1700) x $70 = $11,900

Overcompensation causes the same undesirable effects as a low power factor. It is necessary to select a suitable desired power factor. Based on the literature,[1] when the original (existing) power factor is 0.8 and the desired (corrected) power factor is 0.9, the required capacitor is 0.26 kVAR per kW of load. Thus, the total capacitors required for this plant will be: 1,700kW x 0.26 = 442kVAR

If individual capacitors were used, assuming $25 per kVAR, the installation cost will be: $25 x 442 = $11,050

The resulting payback time is less than one year of operation based on the reduction in penalty charges alone. If the energy savings of the distribution losses were included, the payback time would be less. This example shows that adding capacitors can be of great value. Other potentially lucrative benefits of power factor improvement are that the capacity of the electric system increases, and the voltage drop of the distribution system decreases.

Conclusion

Based on a survey conducted by the authors, a large percentage of public refrigerated warehouses was not aware of their power factors and did not use capacitors to improve their power factors. Although the benefits from improving the power factor may vary with the local utility rate structure for individual plants, a great potential of energy cost savings exists from improving the power factor for more than 50% of the plants surveyed.

Therefore, it is important for each plant manager to understand as much as possible about the electricity rate structure and the status of the plant to achieve high energy efficiency. It is strongly recommended that refrigerated warehouses without capacitors should audit their power factor and the rate structure of their electricity bills.

References

1. Nadel, S., et al. 1992. Energy-Efficient Motor Systems: A Handbook on Technology, Program, and Policy Opportunities. The American Council for an Energy-Efficient Economy.
2. Lobodovsky, K. 1989. "Field measurements and determination of electric motor efficiency." Energy Engineering 86(3): 41-53.
3. Zhang, J. 1999. Energy Saving Technology for Refrigeration Plants. China Machine Press, Beijing.
4. SMACNA. 1984. Energy Conservation Guidelines. Sheet Metal and Air Conditioning Contractors' National Association, Virginia.
5. Zhang, J. and Groll, E. A. 1999. "Survey of energy savings for refrigerated warehouses." Refrigeration Technology and Energy Committee Meeting. The International Association of Refrigerated Warehouses, Washington, D. C., August 1-3.